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Analysis of the process of retention of organic matter in stream ecosystems

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With 3 figures and 1 table in the text

Introduction

Lotic ecosystems are substantially different than most other ecosystems because the continuous unidirectional flow through the system tends to transport matter to downstream reaches. This gives rise to the common erroneous view of streams as conduits or pipes. The process of retention removes matter from transport and makes it available for utilization by stream biota, thus providing a critical link between input and storage.

The retentive properties of a stream are functions of both hydrologic and substrate-related features. Heterogeneity of channel structure and current velocity creates obstructions and slack water areas that enhance retention efficiencies of streams. The retention of a particle in transport is a function of the probability of entrainment of the particle on an obstacle and the frequency of obstacles in the channel (YOUNG et al. 1978). A particle also will be retained in areas where the current velocity is less than the velocity required to keep the particle in suspension. When one of these conditions is met, the particle will be retained until flow conditions change and it is transported downstream.

The influence of riparian vegetation on biological processes in streams extends beyond food resources and habitat. The effects of riparian vegetation on channel structure and organic inputs in streams determine the efficiency with which matter is retained. In this paper, we describe a method for the quantitative assessment of retention of particulate organic matter in streams and identify several major stream retention features that can be influenced by the structure and composition of riparian zones.

Methods

Measurement of retention

The concept of retention includes both the immediate trapping of matter in transport and the subsequent longer-term storage of this material. This study focuses on short-term retention processes on streams and does not address long-term patterns of storage. Retention can be expressed as the difference between the quantity of particles in transport at a given point in a stream and the quantity of those particles still in transport at some distance downstream. This simple measure is of limited comparative value because quantities of introduced particles, experimental reach length, and duration of the measurement may differ. Several approaches may be employed to overcome these limitations. First, reach length can be standardized so that a specific length is used in all measurements. The length of study reaches should be chosen to provide heterogeneity of channel structure and still be sufficiently short so that release and retrieval require only a few hours. Second, time intervals between release and retrieval should be consistent and long enough to represent the trapping or short-term retention. In a preliminary examination of reach retention over a 24-hour interval, we observed no substantial change in retention after three hours. Finally, measurements of retention at different sites or with different quantities of released particles are more comparable if expressed as retention efficiencies, the per cent of the total number of released particles that are retained within the reach, rather than absolute retention, the total numbers of particles retained within the reach.

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Measurement of retention efficiency provides a simple, rapid method of evaluating retention properties of stream reaches; however, a more informative characterization of retention that includes an estimate of the instantaneous rate of retention can be obtained by measurement of exact travel distances of individual particles within the study reach. In this method, a known number of particles are released at the upstream end of the study reach, and all particles not retained are captured at the lower end of the reach. At the end of the release period, the distance traveled by each particle retained within the reach is measured. Retention within a stream reach is then represented by a negative exponential model:

$$T_d = T_o e^{-kd} \tag{1}$$

where T_d is the per cent of total released particles in transport at distance d (m) from the release point, T_o is 100%, and k is the instantaneous rate of removal from transport (instantaneous retention rate). The travel distance of each recovered particle is used to calculate T_d. Particles retained within the study reach but not recovered during retrieval were assumed to be distributed in the same way as particles that were recovered. After determination of the instantaneous rate of retention, the length of stream required for the retention of a given proportion of particles can be calculated by setting T_d to a desired level (e. g. 50% or 90%) in eq. 1 and solving for d. Average travel distance is the inverse of the instantaneous rate of retention (I/K) (Newbold et al. 1981). The instantaneous rate of retention is independent of reach length or quantity of released particles and, therefore, is a more powerful method for comparing retentive properties of stream reaches.

Measurement of leaf retention

We measured the retention of leaves in streams in the Cascade Mountain Range of Oregon using the described methods and evaluated the major components that contributed to the retentive properties of streams. In this study, we used ginkgo (*Ginkgo biloba*) leaves as a leaf tracer. Ginkgo leaves are approximately the same size as leaves of many common riparian trees, are bright yellow in autumn and easily spotted under water, and do not occur naturally along streams in North America. Ginkgo leaves were collected immediately after abscission, air dried, and stored until they were released into streams.

Leaf buoyancy can affect transport dynamics markedly. We soaked all leaves for 12 hours prior to release. After soaking the leaves had a density of $0.95\,g \cdot cm^{-3}$ and were 67% water (w/w). Dry leaves floated on the stream surface, but wetted leaves were approximately neutrally buoyant and were carried by turbulent flow to all depths.

In our study streams, reaches of 50 m were long enough to generally represent the geomorphic structural diversity. Leaf distributions were mapped three hours after the initial release. We determined the number of leaves to be released so that the number retained in the study reach was between 30% and 90% of the total number released; the number retained must be a significant proportion of the total but some leaves should be in transport in all sections of the reach. We found that a release of 3,000 leaves in a 50 m reach generally met these requirements in our study streams. Channel morphology, hydrologic characteristics, substrate types, and leaf characteristics strongly affect retention. The length of the study section and the total number of particles to be released can best be determined by preliminary trial releases.

The method for determination of instantaneous rates of retention can be expanded to incorporate analysis of relative influence of hydrologic and substrate features on retention. We identified the following major components of hydrologic features and substrate structures in streams prior to field investigations:

Hydrologic features	Substrate structures	
Riffle	Sand	Sticks
Pool	Gravel	Large wood
Chute	Cobble	Macroscopic algae
Backwater	Boulder	Moss
Stream Margin	Bedrock	Terrestrial vegetation

When leaves were retrieved, the location of retention (hydrologic feature and substrate type) was recorded for each leaf. The location and approximate area occupied by each substrate type and hydrologic feature were mapped to determine the frequency and proportion of each retention feature within the study reach. The proportion of available leaves retained by each structure was estimated by dividing the number of leaves retained by the structure by the number of leaves in transport at the upstream end of the structure. Relative trapping efficiencies of different retention features were estimated by dividing the proportion of leaves retained by a structure by the total area of the retention structure in the reach.

Flow characteristics of stream reaches greatly influence the retention of coarse particulate matter. Analysis of hydrologic retention may provide useful information in comparative studies of particulate retention. We released fluorescent dye (fluorescein) in all study reaches and measured dye concentrations at the lower ends of the reaches at 30-second intervals. Hydrologic retention curves (dye concentration versus time) were then developed for each reach. Time interval to peak dye concentration or time required for 90 % reduction in concentration may be used as measures of hydrologic retention.

Evaluation of relative trapping efficiencies of specific substrate types enhances our understanding of mechanisms responsible for retention, but does not provide an overall characterization of the physical irregularity of the entire reach. The channel roughness coefficient in the MANNING equation theoretically would provide an excellent measure of physical heterogeneity; however, the MANNING equation was developed for artificial channels with uniform flow, streambeds that are parallel to water surface, and reaches with constant depth, area, and hydraulic radius (BARNES 1967). These assumptions clearly are not applicable in high gradient mountain streams with cascading, turbulent flows. In view of these constraints, we have chosen to express channel irregularity as the ratio of the wetted perimeter to the cross-sectional area of flow. This ratio is a better approximation of the probability of a particle in transport encountering the streambed. Wetted perimeter and cross-sectional area were measured at 5-m intervals through each study reach.

Study sites

Study sites are located in or around the H. J. Andrews Experimental Ecological Reserve on the west slope of the Cascade Mountain Range in Oregon at elevations ranging from 400 m to 1,000 m. This region receives 80 % of its annual precipitation from October through March and is characterized by high winter base flows and low summer base flows. Channel gradients are steep (6—12 %) and substrates are dominated by cobble and small boulders. Stands of large, old-growth Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) dominate most undisturbed watersheds in this area. Large organic debris generated by these stands is a significant geomorphic component of stream channels (SWANSON & LIENKAEMPER 1978). Second-to fourth-order streams were investigated because these streams exhibit a wide range of channel morphology, substrate size, current velocity, and amount of large wood.

Results

Leaf retention curves conformed well to a negative exponential model (Fig. 1). The coefficients of determination (r^2) were greater than 0.90 in more than 80 % of the 20 study reaches examined. An example of a site with a low instantaneous rate of retention (0.014), Grasshopper Creek, and an example of a site with a moderate instantaneous rate of retention (0.067), Lookout Creek, are illustrated in Fig. 1. In Grasshopper Creek, 50 % of the introduced leaves were retained within 50 m, while in Lookout Creek, 96 % of the introduced leaves were retained within the 50 m study reach. In our studies to date, we have observed instantaneous rates of retention ranging from 0.011 to 0.367; these rates of retention represent reaches that require from 210 m to 6 m to retain 90 % of introduced leaves, respectively.

Though leaves were retained at fairly uniform rates at many sites, the presence of wood debris dams had a major influence on reach retention patterns (Fig. 2). For example, the instantaneous rate of retention above the debris dam in Mack Creek was 0.042

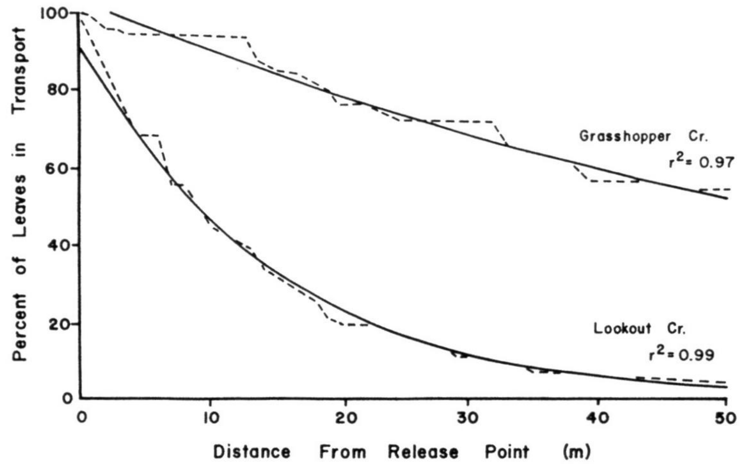

Fig. 1. Per cent of released leaves remaining in transport as a function of downstream distance during summer base flow in third-order streams in the Cascade Mountains of Oregon.

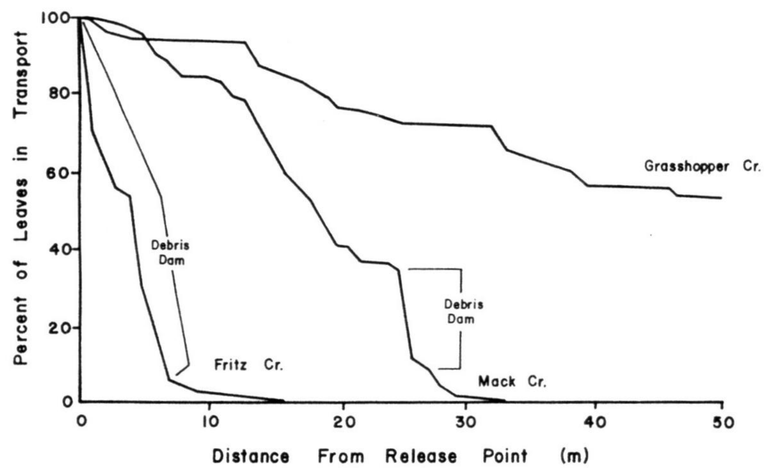

Fig. 2. Influence of debris dams on patterns of leaf retention during summer base flow in third-order streams in the Cascade Mountains of Oregon.

but increased to 0.453 through the debris dam. Stream reaches with major debris dams consistently had greater rates of retention (Fig. 3). Instantaneous rates of retention in sections of reaches with debris dams ranged from 0.402 to 0.453, but were between 0.011 and 0.149 in reaches without debris dams. These rates would represent distances of 15 m to 210 m required for retention of 90 % of introduced leaves in reaches without debris dams but only 5 m to 7 m for reaches with debris dams.

Retention structures differed greatly in their relative efficiency of trapping leaves (Table 1). Leaves were more efficiently retained in riffles than in pools, regardless of sub-

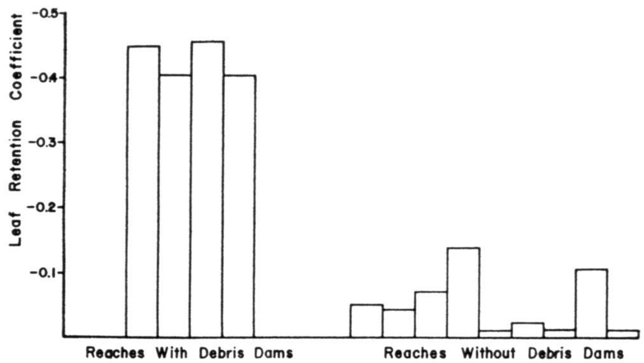

Fig. 3. Comparison of instantaneous rates of leaf retention for reaches with and without debris dams.

Table 1. Relative trapping efficiencies of retention structures in streams. Relative trapping efficiency is expressed as per cent of available leaves in transport retained per m^2 of retention structure.

Retention structure	Trapping Efficiency	
	Riffle	Pool
Gravel to boulder	1.1	0.7
Stream margin	1.3	3.8
Sticks	76.5	30.7

strate type. Substrates along stream margins were more efficient at trapping leaves than the same substrates in the main flow of the stream. Sticks (wood less than 10 cm in diameter) were much more efficient at retaining leaves than any other substrate examined. Trapping efficiency of sticks was between one and two orders of magnitude greater than trapping efficiency of inorganic substrates. Though sticks may appear to be a minor component of channel structure, they greatly enhanve the potential for leaf retention in streams.

Rates of leaf retention were closely related to general hydrologic and structural characteristics of the study reaches. As hydrologic retention (time required for passage of peak dye concentration through a 50 m reach) increased, instantaneous rates of leaf retention were also greater. We also observed that leaf retention rates were greater in reaches with higher ratios of wetted perimeter to channel cross-sectional area.

Discussion

The leaf release method provides an accurate assessment of the retention properties of streams and a useful tool for evaluation of specific retention mechanisms. The techniques described in this paper can be modified to extend the analysis of retention to inorganic sediments, fine particulate organic matter, woody debris, or dissolved nutrients. Streams are efficient at retaining coarse particulate organic matter; several study streams retained 90 % of the released leaves within 10 m and the least retentive stream would have required only 210 m to retain 90 % of the leaves.

Debris dams greatly enhance retention of coarse particulate matter. Debris dams that span the stream channel increase channel width, decrease the effective channel gradient by creating a stepped profile, facilitate the development of side channels, create pools and accumulate fine sediments and sticks (KELLER & SWANSON 1979). The channel widening and creation of side channels increase channel roughness and retention. Debris dams also trap small woody debris that extends out into the flow and creates numerous obstructions. This secondary trapping of small wood is extremely important since sticks exhibited the greatest relative trapping efficiency.

Retention properties of pools and riffles are determined by different mechanisms. In riffles, leaves are trapped on substrate structures that create obstacles in the water column. In pools, leaves are deposited because the current velocity is less than the fall velocity of the particle. Riffles generally retain more leaves than pools, though it is commonly assumed that most organic matter in streams is trapped and stored in pools. This view is largely derived from studies of detrital storage that restrict sampling to the surface layers of sediments (frequently the upper 10 cm). It is important to realize that, geomorphically, pools are erosional sites, created by scour at high flows, and riffles are depositional sites for inorganic sediments. Rigorous, integrated investigations of relative patterns of transport, trapping, and storage of both organic and inorganic matter are essential for the conceptual development of detrital dynamics in lotic ecosystems.

The interaction of hydrologic and substrate features along stream margins increases the potential for retention. Ratios of wetted perimeter to cross-sectional area of flow increase and current velocities decrease as the water becomes shallower toward the stream margins, resulting in greater probability of retention. Through bank stabilization, streamside vegetation facilitates the development and maintenance of margin sinuosity. In streams in the Cascade Mountains, the length of stream margin along a given reach length is approximately 30 % to 40 % greater in coniferous and deciduous stands than in open clearcuts, which suggests a greater degree of margin development in streams in forested watersheds. The protection and stabilization of backwater areas by riparian vegetation is also a major factor in storage of organic matter.

Backwater habitats contained between 110 % and 225 % greater standing crops of organic matter than main channel habitats in streams in coniferous and deciduous forests and clearcuts. Backwaters are generally protected from flushing during moderately high flows and are the primary depositional zones as flows recede after extremely high flow events.

The importance of all major retention mechanisms — debris dams, the ratio of wetted perimeter to cross-sectional area, pool area, the relative amount of stream margin, and the frequency of obstructions — tends to decrease as streams get larger. MINSHALL et al. (1983) found that retention in Oregon Cascade streams decreased exponentially with increasing stream link number. They found similar but lesser decreases in retention in drainages in Idaho, Michigan and Pennsylvania, reflecting the rapid decline in retention structures with increasing stream size. This pattern is not always continuous, however, and local abundance or absence of particular retention structures is more important in determining retention than discharge or stream power alone.

Riparian vegetation is a major determinant of retentive properties of streams. Debris dams and accumulations of sticks and branches are the most retentive features in streams. Rooting by riparian vegetation potentially stabilizes stream banks and enhances development of stream margins, major sites of retention in either pools or riffles. Inputs of logs and bank stabilization both contribute to creation and maintenance of backwaters which are major sites of retention at high flows and major storage sites at all times. The process of retention is a major determinant of the availability of food resources for aquatic biota and this critical process is strongly influenced by the characteristics of the riparian interface between terrestrial and lotic ecosystems.

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